THE IMPACT OF CAPACITOR BANK INSTALLATION ON THE PERFORMANCE OF DISTRIBUTION SYSTEMS - A CASE STUDY

Mohamed A. EL-HADIDY
EETC(*)-Egypt
dr_alhadidy@hotmail.com

Samir A. EZZ EL-ARAB
EETC-Egypt
sezzelarab@moee.gov.eg

Dalal H. HELMI
EETC-Egypt
dalalhelmi@hotmail.com

Mohamed T. IBRAHIM
EETC-Egypt
4m_talaat@yahoo.com

ABSTRACT

Shunt capacitors are installed at substation level, on the medium voltage side, in order to increase the portion of apparent power available for productive use, reduce system losses, maintain voltage at desired levels and enhance better utilization of equipment. During the year 2001/2002, although about 800 MVAr were added to the Egyptian Power Network on the Medium Voltage (MV) side of the High Voltage (HV) substations, it has been noticed that the losses in the distribution network have been increased. This paper presents explanation of this feature through extensive analysis of field measurements supported by theory. Recommendations for improving system performance are introduced.

INTRODUCTION

Rapid development in Egypt, in late seventies and early eighties, led to fast expansion of the Egyptian Electrical Network. The Electric utility then faced a voltage reduction problem at some nodes of the network. A study had been conducted in order to find the technical and economical benefits of reactive power compensation in the network. Since shunt capacitors are employed at substation level for the purpose of voltage regulation, power loss reduction, and increasing equipment utilization [1], the study recommended installation of 1300 MVAR capacitor banks at the MV side of the HV substations in order to maintain acceptable voltage levels and also to correct the power factor in the system.

Since 2001, after reforming the electrical utility in Egypt into five generation, one transmission and seven distribution companies (now nine since 2004), each company continues to study its own sub-network trying to get better performance. The EETC is responsible for HV and EHV (33 kV up to 500 kV) networks; the distribution companies are responsible for MV and Low Voltage (LV) networks (below 33 kV to 0.4 kV). In Cairo zone, part of EETC, about 800 MVAr capacitors have been put into operation during 2001/2002. While the voltage level was improved at nodes where those capacitors were installed, from loss reduction point of view, it was observed that, although losses in EETC network were decreased, losses in Cairo Distribution Company (CDC) networks were increased as shown in Fig 1.

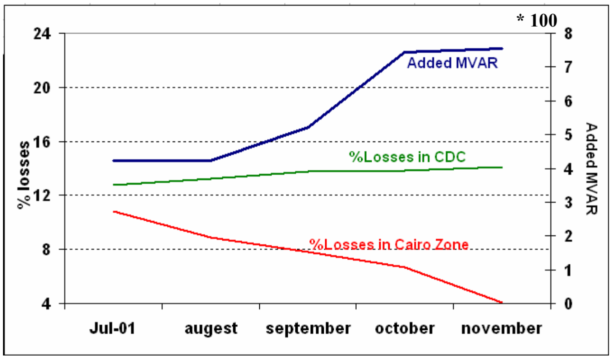

Figure 1: The Effect of Added MVAr on the % Losses in Cairo Zone and CDC Networks

This paper studies the impact of the capacitor banks installation at the MV Bus-Bar (BB) in the HV Sub-Stations (SS) on the performance of the distribution network and its operation parameters, such as: voltage, power factor, active and reactive power, equipment loading, sales and losses. Case studies were conducted using Digital Disturbance Recorders (DDR) to capture measurements just before and after the switching of capacitor bank, and to help in the analysis of the measurements. A theoretical explanation is then provided to support the obtained study results. Conclusions and recommendations for better performance are introduced.

FIELD MEASUREMENTS

Figure 2 shows a general schematic diagram for the system under study. The left hand side part represents the generation and transmission network (upstream) while the right hand side represents feeders to the distribution network (downstream).

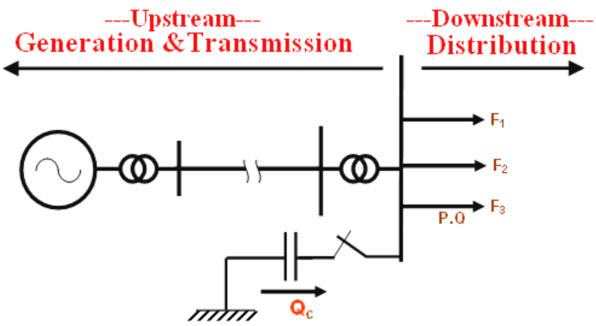

Figure 2: Schematic Diagram for the Power System

(*)EETC-Egyptian Electricity Transmission Company

It is well known that, when a capacitor is connected to a certain node in a power system, it injects a value of reactive power (Q_c) at this node, depending on its capacity. This leads to some increase in the voltage level of this node. Generally, in the Egyptian HV SS, two-step switched capacitor banks (1.8 MVAr each) are installed at MV BB for each transformer.

To investigate the feature under consideration, two transformers in two different 66/11kV SS, and their feeders represent the case studies of this work. The first case study includes a transformer (T1) with feeders (F1), (F2) and (F3); The second case study has a transformer (T2) with feeders (F4), (F5), (F6) and (F7).

The purpose of the field measurements is to study the effect of capacitor switching-on to the system on the operating parameters of the network such as: voltage (V), current (I), power factor (pf), active power (P), reactive power (Q) and losses (L) in both upstream and downstream. This can be achieved by recording this data for both the transformers and their feeders just before and after the moment of the capacitor switching. The time difference between the readings before and after this moment should be small enough so that the change in the load of the equipment is negligible between the two readings.

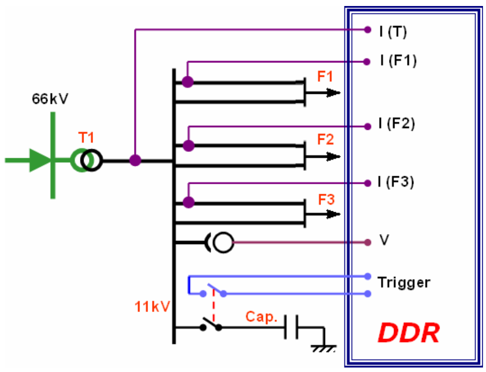

Figure 3: DDR Connections for case study no.1

Field measurements for the 11kV BB voltage, and the currents through feeders were recorded using portable DDR. The DDR has 16 analogue inputs, 8 voltage channels and 8 current channels. Events (digital inputs) were used to trigger the DDR when the capacitor bank is switched on/off to the system. The main reason for the use of DDR is to capture the changes in the voltages and currents due to the capacitor switching before any variation in the load takes place. The recorder has memory to capture pre-incident data so, the signals, just before and after the capacitor switching, are recorded. The analysis software of the DDR is used to calculate the values for the phase values of V, I, pf, P and Q in both the transformers and the feeders.

The waveform records of the voltages and currents, also the calculated channels for V, I, pf, P, and Q for the transformer T1 and feeder F2 are shown in Figures 4 and 5 respectively. Those values are corresponding to the left hand side and the right hand side cursers for the signals before and after the capacitor switching respectively. Similar quantities are calculated for all feeders.

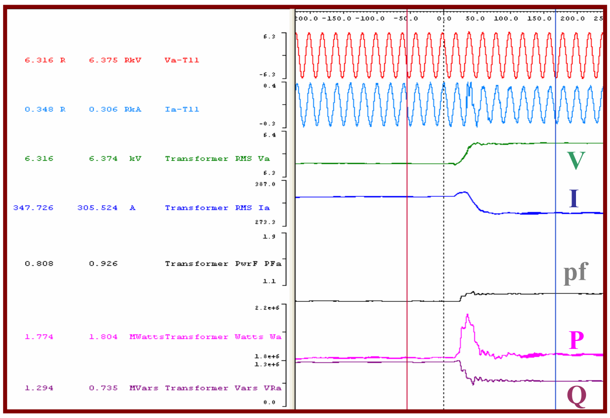

Figure 4: Recorded and Calculated Channels for T1

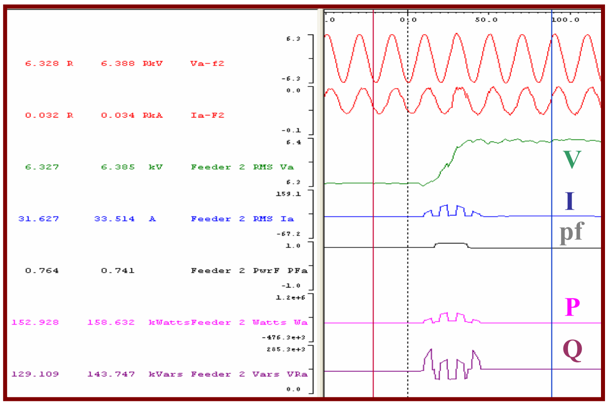

Figure 5: Recorded and Calculated Channels for F2

The same analysis is done for the second case. Figures 6 and 7 show the recorded and calculated channels for T2 and F7 respectively.

For each of the transformers and the feeders, the relative change in V, I, pf, P, Q and L are calculated. The relative change in a quantity (V as an example) is defined as the difference ΔV between the value of the voltages after and before the capacitor switching (V and V_o respectively), and is given by: $\Delta V / V_o = 100 * (V - V_o) / V_o$ %

Similar equations are used for the other variables (I, pf, P, and Q). As the metal losses are proportional to the square of the current, the percentage relative change in losses (L) due to capacitor switching is calculated as follows:

$$\Delta L/L_o = 100 * (L - L_o)/L_o = 100 * (kI^2 - k I^2_o) / kI^2_o$$
$$= 100 * (I/I_o)^2 - 100 \quad \%$$

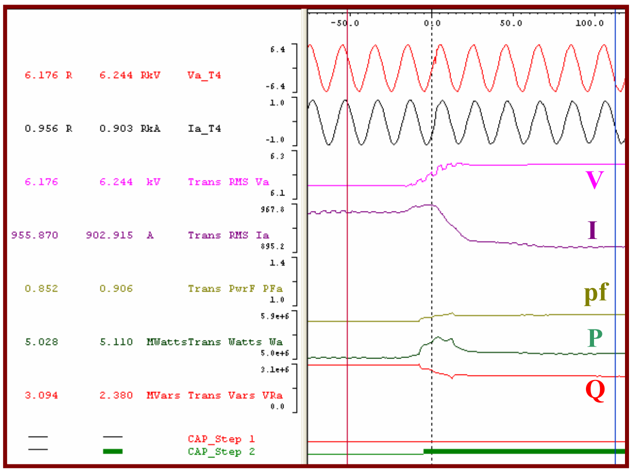

Figure 6: Recorded and Calculated Channels for T2

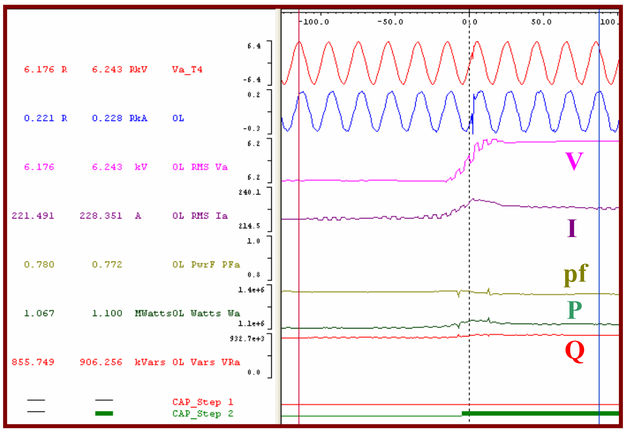

Figure 7: Recorded and Calculated Channels for F7

Table 1. Calculated Relative Changes for Case 1

Relative changes	T1	F 1	F 2	F 3
$\Delta V/V_o$ %	0.93	0.93	0.93	0.93
$\Delta I / I_o$ %	- 11.6	0.72	4.3	2.3
$\Delta pf / pf_o$ %	14.8	-1.62	- 2.2	- 1.0
$\Delta P / P_o$ %	2.7	0.05	3.05	2.2
$\Delta Q / Q_o$ %	- 40.2	6.24	7.81	5.3
ΔL/Lo %	- 21.9	1.45	8.78	4.65

Table 2. Calculated Relative Changes for Case 2

Relative changes	T2	F 4	F 5	F 6	F 7
$\Delta V/V_o$ %	1.08	1.08	1.08	1.08	1.08
$\Delta I / I_o$ %	-5.97	1.38	1.74	2.27	2.77
$\Delta pf / pf_o$ %	6.46	-0.43	-0.95	-1.17	-1.41
$\Delta P / P_o$ %	1.17	2.06	1.94	2.24	2.52
$\Delta Q / Q_o$ %	-23.3	4.96	5.16	6.55	5.96
ΔL/Lo %	-11.6	2.77	3.51	4.6	5.63

The results of these calculations are shown in Table 1 and Table 2 for the case studies 1 and 2 respectively.

ANALYSIS OF THE FIELD MEASUREMENTS

From Tables 1 and 2, it is clearly shown that the connection of the capacitors to the MV BB in the HV SS leads to the following results:

1. Decrease of the transformer (upstream) current by 11.6 % for T1 and about 6 % for T2, while the load currents (downstream) increased by values ranging from 0.72% (F1) to 4.3% (F2).
2. While the pf of the transformer is improved by 14.8 % for T1 and 6.5 % for T2, the pf of the loads are decreased by values between 0.43 % (F4) and 2.2 % (F_2).
3. The active power (sales) is increased for both upstream by 2.7 % for T1 and 1.2 % for T2 and increased downstream by different values: 0.05% (F_1) to 3.05% (F_2).
4. A drastic decrease of 40 % for T1 and 23 % for T2 in reactive power had occurred to the transformers; on the contrary the reactive power is increased in the loads by a ratio between 5.3% (F_4) and 7.8 % (F_2).
5. The metal losses in transformer (upstream) are decreased by about 22 % for T1 and 11.6 % for T2, while in the feeders (downstream) the losses increased by ratios ranging from 1.5 % (F_1) for 8.8 % (F_2).

Result 5 above is of great concern since it proves what was noticed about the increased losses in CDC after putting 800 MVAr into operation in the year 2001/2002. In brief, the location of the capacitor divides the network into two sides: upstream where good effects on I, pf, P, Q and L are accomplished; in the downstream it causes negative effects on I, pf, Q and L. Generally, voltage and sales are improved for both sides.

THEORETICAL EXPLANATION

The change of the active and reactive power of a load is affected by the change of the voltage applied to this load. The loads are modeled by different characteristics in different power system analysis programs. For steady state studies, loads are represented by their static characteristics. Generally, for small variations in the supply voltage (ΔV) and frequency (Δf), the changes in active power (P) and reactive power (Q) of load demand can be given by the following expressions [2,3]:

$$\Delta P = (\partial P/\partial V)\Delta V + (\partial P/\partial f)\Delta f$$
$$\Delta Q = (\partial Q/\partial V)\Delta V + (\partial Q/\partial f)\Delta f$$

Where,

$\partial P/\partial V$, $\partial Q/\partial V$ are the "*voltage regulation coefficients*" for P&Q respectively; and

$\partial P/\partial f$, $\partial Q/\partial f$ are the "*frequency regulation coefficients*" for P & Q respectively.

For system in steady state, we can assume negligible variation of the frequency, i.e. Δf = 0. Then,

$$\Delta P = (\partial P/\partial V)*\Delta V$$
$$\Delta Q = (\partial Q/\partial V)*\Delta V$$

The values of the Voltage Regulation Coefficient for Active Power (VRCP) and the Voltage Regulation Coefficient for Reactive Power (VRCQ) depend mainly on the type of the load: light, domestic, industrial, inverter or rectifier load….etc. Figure 8 shows the relationship between P, Q, ∂P/∂V and ∂Q/∂V for a composite load consisting of the following components [2]:

- Small Induction Motors 34 %
- Large Induction Motor 14 %
- Lighting 25 %
- Rectifiers, inverters and heating devices 10 %
- Synchronous motors 10 %
- Network Losses 7 %

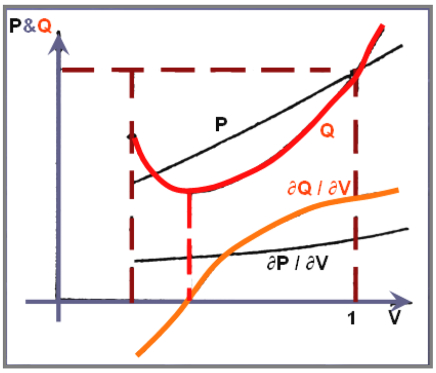

Figure 8: Approximate Static c/c^s of Composite Load as Functions of voltage

For this composite load, VRCQ and VRCP (expressed in relative units) usually range from 1.5 to 3.5 for the reactive load component, and from 0.3 to 0.75 for the active load component. This means that in the best case where VRCP is max. (0.75) and VRCQ is min (1.5), we can expect that the relative change in the reactive power is double the relative change of the active power. In the worst case, this value may reach 3.5/0.3, i.e. more than ten times. For individual load elements, VRCP and VRCQ usually vary within wider limits than for the composite load.

In the case studies of this work, to obtain the regulation coefficients of the loads under study, data of Tables 1 and 2 are used to calculate ∂P/∂V, ∂Q/∂V and ∂Q/∂P as shown in Table 3.

For each of the loads under study, VRCQ is always higher than VRCP. While the value of VRCP ranges form 1.79 (F5) to 3.3 (F2), VRCQ ranges from 4.6 (F4) to 8.4 (F2). The ratio of VRCQ to VRCP ranges between 2.4 (F7) and 2.9 (F6). (N.B. the values of 0.05 for VRCP and 124.9 for VRCQ of load F1 are excluded).

Table 3. Regulation Coefficients of the Loads under Study

		Δ P/ΔV	ΔQ/Δ V	ΔQ/ΔP
Case1	**F1**	0.05	6.75	124.9
	F2	3.3	8.44	2.59
	F3	2.38	5.73	2.41
Case2	**F4**	1.9	4.57	2.41
	F5	1.79	4.76	2.66
	F6	2.06	6.04	2.93
	F7	2.32	5.5	2.37

CONCLUSIONS AND RECOMMENDATIONS

Installation of shunt capacitor banks on the medium voltage bus at the high voltage substations leads to the improvement of the voltage level and sales at this point. While the pf, loss ratio and equipment utilization are highly improved in the upstream, they get worsened at the downstream. The main reason behind this is that the VRCQ is higher than VRCP for the loads.

Capacitors can be applied on the electrical system downstream of the metering point and have the same effect on the upstream power factor. However, it is generally advisable to place them as close as possible to the inductive loads (e.g. at low LV feeder ends) to minimize power losses and voltage drops on the MV and LV feeders in the distribution network. The cost of LV capacitors is extremely less than the cost of the HV ones.

Co-operation between transmission and distribution companies is vital in this field. Both companies can share the cost and share the benefits of the best sizing and location of the capacitor banks.

The use of the DFR in the way in which it is used in this work enables studying the effect on the load considering the effect of the capacitor alone, despite the ever changing equipment load.

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